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Review

Scour Protection Measures for Offshore Wind Turbines: A Systematic Literature Review on Recent Developments

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Abstract: Offshore wind energy is considered as one of the most promising resources of clean and renewable energy to replace fossil fuels. Additionally, its cost is expected to be lower than onshore wind energy as the technology matures. Offshore wind turbines (OWTs) normally operate in harsh ocean environments, which could impact their structural integrity. Scour erosion around foundations of OWTs can substantially change the overall stiffness of these structures and shorten their lifetime. Currently, there are a limited number of studies on countermeasures and their engineering requirements for decreasing the scouring effect; this is due to their different hydraulic circumstances, such as their stability, reliability, and resistance capacity. To this end, advancements in scour protection measures in the offshore energy sector are evaluated in this paper through a thorough and critical review following the PRISMA systematic literature mapping approach. This includes 68 papers on scour protection and over 30 scour protection designs for various types of wind turbine foundations. Here, we aim to provide an overview of the latest scouring protection measures and their comprehensive assessment, as well as their prospects and future challenges. The findings of this study will provide key insights into scour protection measures for OWTs and will subsequently contribute to the future growth of the offshore renewable energy sector.

Keywords: offshore wind turbine (OWT); offshore renewable energy; scour protection; scour; monopile foundation; jacket foundation; systematic literature review

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1. Introduction

Anthropogenic activities, notably deforestation, combustion of fossil fuels, and industrial processes, are chiefly responsible for precipitating global warming and climate change, thereby posing a substantial existential threat to human existence. These phenomena have induced unprecedented alterations in Earth's climate dynamics, which are evident in escalating temperatures, heightened occurrences of extreme weather events, glacial retreat, and rising sea levels. Such manifestations underscore the urgent need for mitigation strategies to address this critical global crisis [1]. In such a context, an accelerated transition towards low-carbon energy systems is imperative [2]. Additionally, the energy demand in densely populated coastal areas is usually higher compared to other areas, as nearly 40% of the global population resides within 100 km of the coastline [3]. Given the characteristics of widespread, inexhaustible, and clean nature, offshore wind energy is considered one of the most promising sources for clean and renewable energy. Offshore wind energy has the advantage of higher energy density, lower turbulence, lower wind shear, and less land occupation compared to onshore wind energy [4]. Its cost is expected to be lower than onshore wind energy as the technology matures [5]. Figure 1 shows the total installed capacity of offshore wind energy within the past ten years and indicates a strong growth and investor confidence in global context [6]. The global wind installation is expected to surpass 3500 GW (with 500 GW offshore) by 2030 [7].

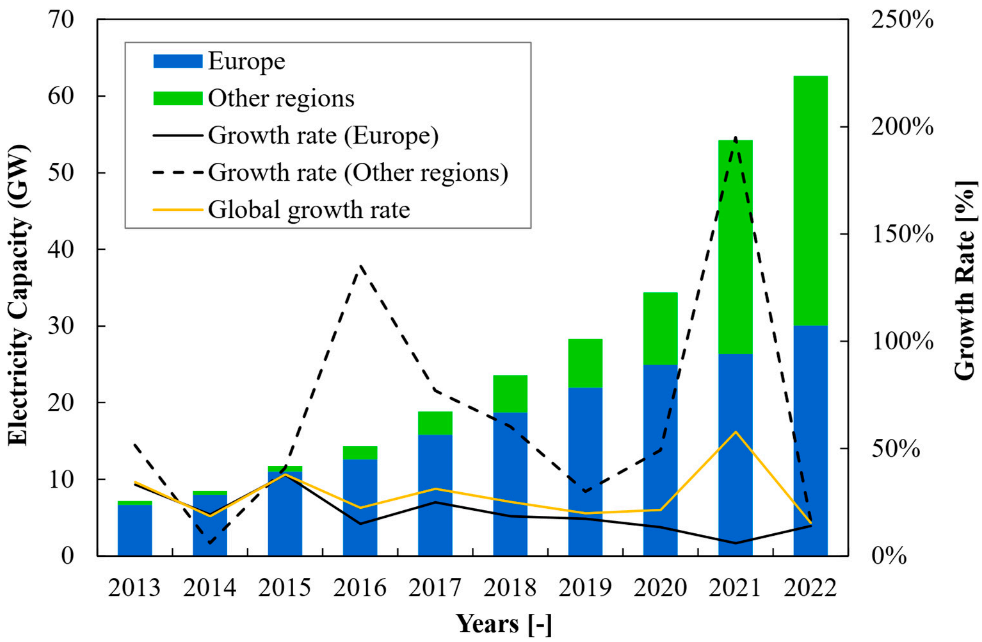

Figure 1. Cumulative installed capacity of offshore wind energy from 2013 to 2022 (data sourced from IRENA [6]).

The foundation design of offshore wind turbines (hereinafter referred to as OWTs) plays a vital role in their overall design. Typically, the foundation costs account for 25% to 34% of the overall costs for OWTs, with a considerable part being related to scour protections [8]. Foundations for OWTs can be classified broadly into two main types: fixed foundations and floating foundations. Figure 2 shows, from left to right, seven types of fixed turbines' foundations (gravity-based, bucket, monopile, tripod, tripile, twisted jacket, and jacket), and nine types of floating turbines (Ideol in a floating cylinder, Ideol in a floating square, Windfloat, Winflo, Blue H Tlp, floating Haliade, PelaStar, Advanced Spar, and Hywind). The applicable water depth is generally 0–50 m for fixed foundations and more than 50 m for floating foundations [9]. Floating platforms are held in place with a system of mooring lines (likely chains) [10], and they can be deployed below 100 m, even 200 m water depth [11]. It is found that scouring is not an issue for conventional drag embedment anchors because they are completely buried in the seabed [10]. However, scour is detected as a main uncertainty in the design of fixed-foundations OWTs [12]. As is evident in Figures 3 and 4, floating foundations have not been widely constructed thus far, whereas fixed foundations, especially monopile foundations, are relatively mature. Overall, the monopile foundation is the most widely used foundation type, and the jacket foundation has seen the most significant growth over the past years. To this end, this systematic literature review focuses on scour protection approaches for fixed foundations of OWTs, particularly monopile and jacket foundation types.

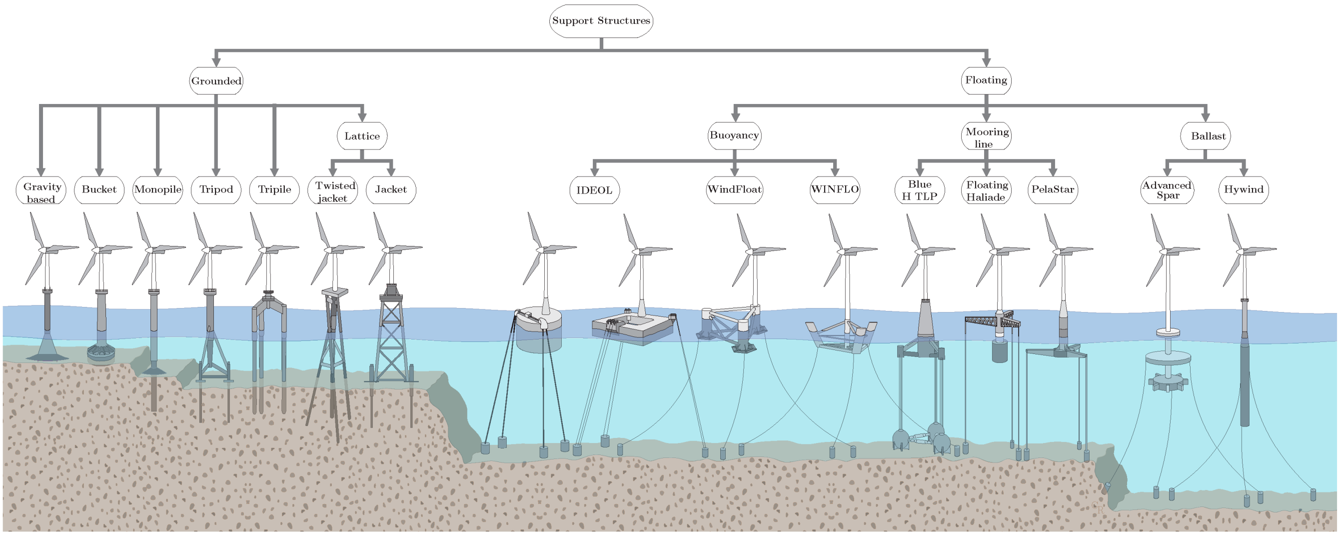

Figure 2. Foundations applicable to different water depths (from reference [13]).

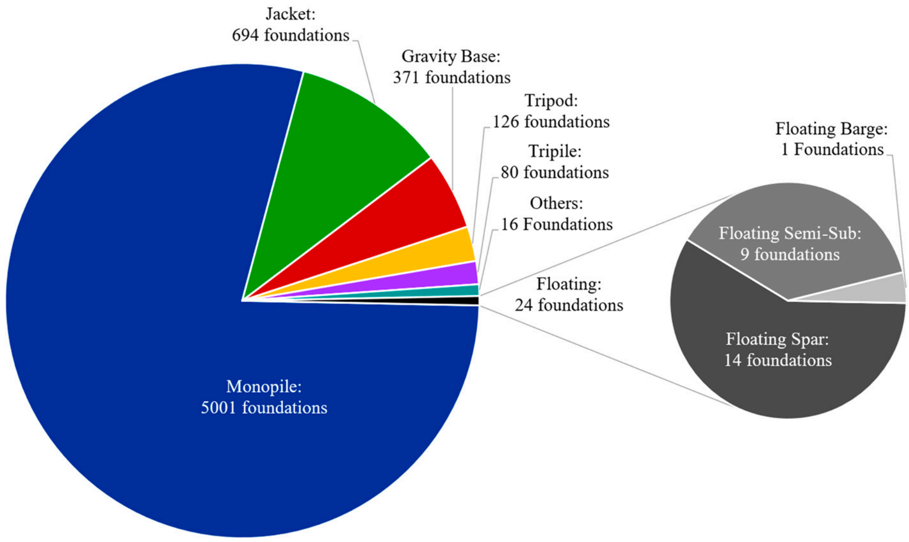

Figure 3. Statistics for European offshore wind turbine foundations (data sourced from WindEurope [14]).

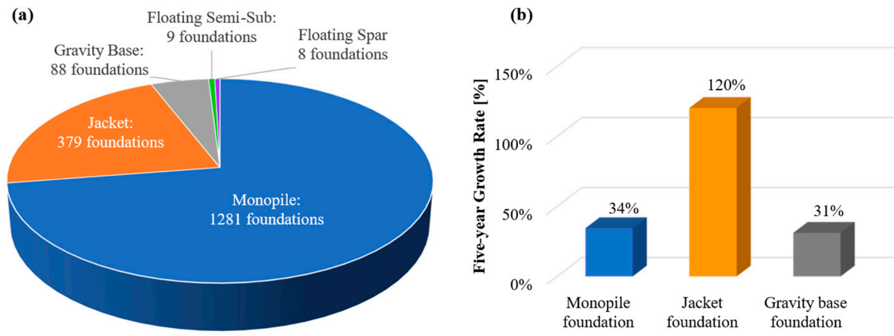

Figure 4. Growth of different foundation types from 2017 to 2022 in Europe (data sourced from WindEurope [14,15]): (**a**) increasing numbers of different foundation types; (**b**) growth rate of fixed foundations.

Placement of a structure along the coastline or offshore environment will ultimately change the flow pattern around and lead to complex interactions between fluid, sediment, and the structure [16]. The sediment transport around the structure will therefore increase and thus lead to scour. Scour refers to the erosion of sediment around the foundation structure. Scour is one of the main causes of failure in OWT structures with fixed foundations in marine environments. The scouring phenomenon around OWTs considerably threatens the longevity and stability of such structures and consequently restricts their further growth. Li et al. [17] reported scour mechanisms around OWTs along with empirical prediction formulae to assess scour depths for such foundations. Local scour is identified as the main element for scouring in fixed foundations [18] while edge scour is considered the critical problem causing the failure of scour protection measures [19,20].

Currently, there are a limited and scattered number of studies on the countermeasures (and their technical requirements) for lessening the scouring effect; this is due to their to varied hydraulic situations, including stability, reliability, and resistance capacity. Previously published literature reviews (such as [21,22]) are limited to monopile foundations only and subsequently have failed to provide a comprehensive overview of scour protection measures for OWTs (including the effectiveness and ecological impact of scour protection measures with different foundation types). Therefore, there is a need to credibly summarize scour protection measures for OWTs, encompassing related research advances made in recent years to develop an integrated portfolio of scour protection measures for OWTs and inform future research and policy needs. To fill this void, here, a systematic review of the literature is conducted to highlight existing scientific knowledge, practices, tools, and research works on scour protection measures for OWTs and to reveal the way forward for future research works in this context.

The rest of the paper is structured as follows: Section 2 presents the methodology adopted in this study. Recent developments on scour protection measures and the ecological influence of scour protection are reviewed and discussed in Section 3. Section 4 discusses and highlights potential research gaps. Section 5 summarizes the main takeaways from this study.

2. Systematic Review Method

We conducted a systematic literature review following the standard systematic mapping approach, i.e., Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [23]. In this study, Web of Science and Scopus databases were explored to identify relevant studies using defined search terms and inclusion and exclusion criteria. In the initial screening, the specific search terms or keywords were 'Offshore Wind Turbines', 'Offshore Wind Foundations', 'Offshore Wind Farm', 'Scouring', 'Monopile Foundation', 'Jacket Foundation', 'Bucket Foundation', 'Gravity Base Foundation', 'Tripod Foundation', 'Tripile Foundation', and 'Offshore Ecology'. The search was undertaken between September and November 2023.

A total of 494 published papers were identified by conducting the keyword search process. Following the completion of the initial phase of screening and the identification of relevant research papers, we reviewed each paper's title and abstract by employing inclusion and exclusion criteria to exclude non-qualifying papers. In Table 1, the inclusion and exclusion criteria adopted in this work are presented. In this stage, only relevant peer-reviewed documents published in English language were advanced to the next stage. Overall, a total of 430 publications were excluded from the review following the criteria presented in Table 1. Following the final screening of the title and abstract of each paper, a total of 64 papers were retained for full-text review and further analysis. In Figure 5, each review process step followed in this study is shown, showcasing the decision parameters.

Table 1. Inclusion and exclusion criteria adopted in this study.

Criteria	Include	Exclude
Language	Research papers published in English	Papers published in languages other than English
Publication Year	Published from January 2003 to November 2023	Published before January 2003
Publication source	Peer-reviewed articles	Non-peer-reviewed papers
Focus/Content	Studies focused on scour protection measures for OWTs	Studies focused on scour protection measures for other structures such as bridge piers, seawalls, etc.

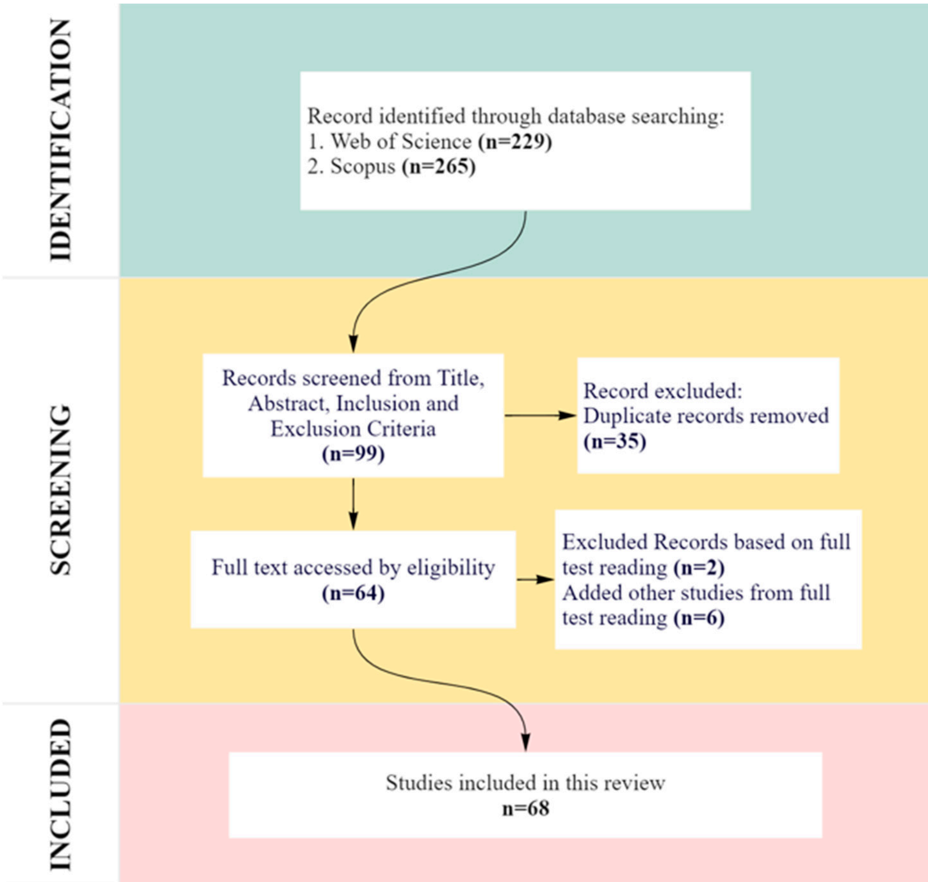

Figure 5. Flow chart of the inclusion and exclusion process for the literature review following the PRISMA framework.

In Figure 6, the growth of research on scour protection measures for OWTs over time is presented, showing 650% growth in the number of papers published in the period 2020–2023, compared to the number of publications in the period 2004–2007. As is evident from Figure 6, most of the literature on scour protection measures has been published in recent years, wherein authors proposed new measures or hypotheses which still need to be validated on a larger scale.

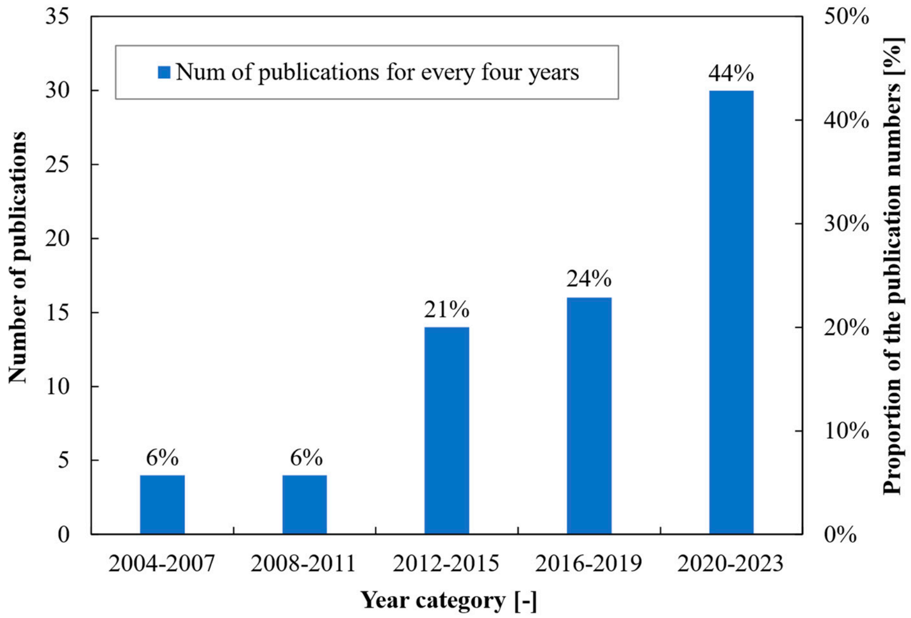

Figure 6. Publications for every four years.

3. Analysis of Scouring Protection Measures

3.1. Monopile Foundation

Monopile foundations are normally installed at 0–25 m water depth [9]. The fundamental scour mechanism around a monopile foundation is explained in Figure 7, highlighting the interaction between water flow, the ground material, and the monopile itself. The flow goes down with increasing water pressure after reaching the front of the monopile. Then, a horseshoe vortex is formed in front of the monopile with streamlines contracted at the sides of the monopile. Additionally, pairs of counter-rotating vortices are observed as vortex shedding occurs at the leeside of the monopile and produces a symmetrical scour pit [24,25]. Nevertheless, water flow has no single direction in marine environments, and a worse scour phenomenon is probably formed under complex hydraulic conditions.

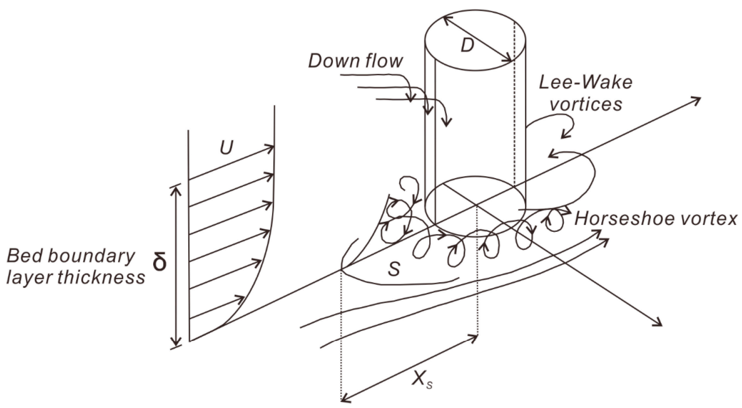

Figure 7. Scour phenomenon around a monopile (from reference [26]).

In the following subsections, typical scour protection measures for monopile foundations are discussed as follows: Section 3.1.1 examines riprap protection measures, followed by a discussion on ground improvement protection measures in Section 3.1.2. In Section 3.1.3, flow altering scour measures for monopile foundations are highlighted.

3.1.1. Riprap Scour Protection Measures

Riprap, as shown in Figure 8, is the most widely used and accepted scour protection measure for OWTs; it has the advantages of low cost and material availability. Up to now, it has been further studied via stone size design, damage analysis, and reliability assessments, as in references [27–29]. Based on applied design concepts, riprap protection for OWTs can be categorized into four major groups: (i) the static approach, which allows no movement for the top-layer stones [30]; (ii) the dynamic approach, which allows limited movements of top-layer stones [31]; (iii) the wide-graded protection approach [32], and (iv) the cemented approach [33]. Additionally, it is possible to design riprap protections by optimizing rock size and density, number of layers, and width of cover [34]. The failure mechanisms of the riprap protection mainly include shear failure, winnowing failure, edge failure, and bed form induced failure [35].

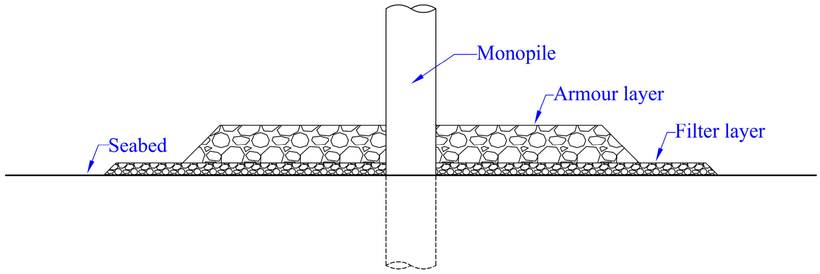

Figure 8. Typical design of a riprap protection measure.

The riprap design of OWT scour protection measures originates from the bridge pier riprap design, which is relatively mature. However, it should be noted that there exists different hydrodynamics between the inland rivers and offshore areas. Esteban et al. [36] employed an empirical formula for riprap design, which was originally applied to fluvial and coastal systems for the first time for five OWTs and compared with field measurements. The authors then concluded that De Vos empirical methods [30,31] can be applied for stone selection for scour protection for OWTs.

Den Boon et al. [37] described and calibrated the Opti-Pile design tool, a spreadsheet developed by HR Wallingford to predict the depth and width of the scour hole, bed-level movements, and static and dynamic riprap. The Opti-Pile design tool was developed for monopiles in European shelf seas and uses a stability parameter Stab to determine the damage category. The calibration for this tool was principally based on a set of physical model tests including static and dynamic designs. The dynamic design in this case allowed for the development of a large scour pit for the seabed around the base of the monopile (except topsides) and then filled with a wider grading rock. When compared to other existing tools, the Opti-Pile design tool showed an overall improved performance in predicting scour depths around monopile foundations, based on the data collected from full-scale measurements from the Scroby Sands Offshore Wind Farm [38]. Whitehouse et al. [39] performed a series of flume experiments to investigate scour depths and the stability of scour protection measures in relatively shallow water (about 4 m deep water). Authors argued that the stability parameter Stab was not closely related to the maximum damage for the conditions tested in their work. Later, in 2016, a dynamic protection strategy using the Opti-Pile design tool was applied to Nordergründe offshore wind farm and validated successfully in a highly morphodynamic environment [40]. It should be noted, however, that the detailed design parameters of the Opti-Pile design tool are not freely available to users.

Founded on a literature review focusing the design aspects and field measurements, Matutano et al. [41] reported that as a rule of thumb, the thickness of the armor layer should be at least twice the median stone diameter D_{50}; they also suggested the extension size of riprap protection to be between a half to a quarter of a wavelength [27,42]. Furthermore, the dimensionless wave height parameter H_0 was calculated and suggested initial values in the range between 6 to 15.

De Vos et al. proposed basic empirical design guidelines for a static approach in 2011 [30] and dynamic approach in 2012 [31]; see Equation (1) for the static approach. The design equation for the static approach was derived from physical model tests under regular wave attack and a steady current. Equation (1) was designed to calculate the required stone size for static stability and can be applied to both design a new scour protection and to verify whether a given protection design is statically stable or not. For the former, an iterative process is required through estimating the value of the Median stone diameter D_{50} and comparing $\tau_{cr,pred}$ with the critical bed shear stress of the top layer $\tau_{cr,top\ layer}$. Design diagrams for the threshold of incipient motion of cover stone [43] can be used for verification.

$$\tau_{cr,pred} = 83 + 3.569\tau_c + 0.765\tau_w \quad (1)$$

where $\tau_{cr,pred}$ is the required critical bed shear stress of the stone size $D_{67.5}$ of the top layer; τ_c is the current-induced bed shear stress; and τ_w is the wave-induced bed shearstress. Shear stress refers to the force per unit area acting parallel to the surface of a material, causing it to deform or slide along a plane. Shear stress and friction are intimately related concepts in the context of material behavior.

Although the static approach reduces the required stone size compared with traditional methods towards broad marine conditions [31], it remains a waste that the displacement of the top layer stones is considered as a damage in this static approach. Dynamic approach allows the development of an acceptable dynamically stable profile in the riprap protection, which is proved to be feasible [44], see Equation (2). It is an optimization of the design procedure that is achieved by adding a damage factor and the number of waves (an indication of the development of damage) to the design formula [45] as follows, which leads to a reduction of 20% to 80% of the required stone size when compared to the static approach.

$$\frac{S_{3D}}{N^{b0}} = a_0 \frac{U_m^3 T_{m-1,0}^2}{\sqrt{gd}\left(s-1\right)^{3/2} D_{n50}^2} + a_1\left(a_2 + a_3 \frac{\left(\frac{U_c}{w_s}\right)^2 \left(U_c + a_4 U_m\right)^2 \sqrt{d}}{g D_{n50}^{3/2}}\right) \quad (2)$$

in which S_{3D} is the damage number; N is the number of waves; b_0 is 0.243; a_0 is 0.00076; U_m is the bottom orbital velocity; $T_{m-1,0}$ is the energy spectral wave period; g is the gravitational acceleration = 9.81 m/s^2; d is the water depth; s is the relative density of the stones; D_{n50} is the nominal stone diameter; a_2 is -0.022; a_3 is 0.0079; U_c is the depth averaged flow velocity; and w_s is the fall velocity. As for parameters a_1 and a_4,

$$a_1 = 0 \text{ for } \frac{U_c}{\sqrt{gD_{n50}}} < 9.2 \text{ and waves following the current;}$$

$$a_1 = 1 \text{ for } \frac{U_c}{\sqrt{gD_{n50}}} < 9.2 \text{ and waves opposing the current;}$$

$$a_4 = 1 \text{ for waves following the current;}$$

$$a_4 = \frac{U_r}{6.4} \text{ for waves opposing the current.}$$

where U_r is the Ursell number, i.e., a dimensionless parameter used in fluid dynamics to characterize the nonlinearity of surface gravity waves on a fluid surface.

Equation (2) was developed by De Vos et al. in 2012 [31] based on flume experiments with irregular waves together with a steady current. It is also evident from Equation (2) that waves opposing the current may result in larger damage to the structure. It should be noted that the riprap protection in this dynamic approach was constructed before scouring and was not related to the scour pit backfilling. The damage number S_{3D} was extended and analyzed through a new set of flume experiment data by Fazeres et al. [28], which was outside the range of the original dataset for developing Equation (2). Authors explained the behavior of the damage number and considered that the damage number is more accurate than the stability parameter Stab when describing the stability of dynamic scour protection.

The static and dynamic design approaches presented above are considered as narrow-graded protection techniques which include an armor layer and a filter layer. The voids in the armor layer, however, may cause the washout of finer particles. In such a context, a wide-graded riprap (a single stone layer with a very extensive granulometric curve) approach could be found more effective compared to the narrow-graded approach [32,46], particularly given the characteristics of a wide-graded riprap approach offering high erosion stability. Founded on a suite of large-scale experiments, Schendel et al. [32] concluded that bigger stones providing shelter to relatively smaller gravels and voids in wide-graded riprap protection were overall smaller compared to those reported in narrow-graded riprap protection. More recently, Nielsen and Petersen [43] noted the application of the single protection layer of wide-graded stone materials in field conditions. However, deterministic design guidelines for the wide-graded riprap protection measure are yet to be developed prior to full-scale design and implementation of such schemes for scour protection of OWTs [47].

To achieve stable scour protection, scour protection failure beyond the design phase should be considered, including the loss of subsoil and edge scour. Riprap sinking induced by loss of subsoil is a common problem noticed and reported from investigations of sites such as Horns Rev 1 Offshore Wind Farm [48], Offshore Windpark Egmond aan Zee [49], and Arklow Bank Offshore Wind Farm [19]. Full-scale and high-resolution measurements were conducted for seabed and scour measure approximately 80 foundations in the Horns Rev offshore wind farm, as reported by Hansen et al. [48]. These authors concluded that the riprap sinking can be up to 1.5 m, highlighting that sand transport through filters and the armor stones was the main reason for it. Authors suggested applying a thicker filter layer with a higher gradation for the riprap protection or carrying out frequent surveys and then applying new stones if necessary [48]. Based on physical model tests in steady currents, the mechanism causing the sinking of a riprap has been identified in work by Nielsen et al. [50] as horseshoe vortex penetration and high flow velocities and turbulences near the base sediment under the riprap. Previous works such as reference [51] concluded that the base sediment under the scour protections was mobile under their tested extreme current conditions, and the authors argued that there is a strong possibility of sediment being mobile under comparatively less extreme conditions when considering the effect of wave actions. In addition, a set of non-dimensional parameters was proposed by researchers [52] for formulating the initiation of the motion beneath the scour protection and the sinking of it. Furthermore, Nielsen et al. [53] studied the motion process of the former to quantify and compare the critical mobility number of the sediment beneath scour protection under different hydrological conditions and provided design diagrams for the threshold of the sediment incipient motion.

A detailed comparison between the experimental work [50] and field observations in Horns Rev offshore wind farm was also made, which revealed the potential cause of the sinking of the entire protection—the upward movement of the bed sand adjacent to the monopile base [52]. Nevertheless, another study [54] found the removal of the sediment adjacent to the foundation and infilling of the sediment materials from the immediate seabed were the two main sinking mechanisms of a riprap exposed to waves, of which the latter was found to be the stronger one. Regarding the case of combined waves and current, there was no particular increase in the actual sinking values compared with waves-only or current-only cases [54]. Alongside water, another type of sinking was found to be induced by vibration [55]. The authors of [55] noted that the subsidence caused by a convective domain from vibration can subside and densify soil and then mitigate flow-induced subsidence through limiting riprap edge scour and winnowing failure, indicating that vibration frequency is positively associated with subsidence speed and vibration amplitude dominates the subsidence degree.

The edge scour of the riprap protection was found to be up to 2.7 m outside the cover stone area according to the surveys of Offshore Windpark Egmond aan Zee. The falling apron effect occurs after the formation of the edge scour pit, which leads to deformations and failure of the scour protection. A study determined the flow mechanisms governing edge scour and indicated that by lengthening the filter in the direction of the main tidal axis and applying a relatively smaller rock in the filter layer, the edge scour can be effectively mitigated [20].

The riprap scour protection is an integral part of OWTs, which may interact directly or indirectly with the wind turbine structure and thereby influence the reliability of the structure. For instance, it has been found that riprap protection has a slightly positive impact on the monopile behavior in an ultimate limit state and fatigue limit state and can reduce the cross-sectional rotation up to 18% in a mudline in a serviceability-limited state [56]. In a recent work by Yin et al. [57] on riprap protection for a monopile foundation using a novel coupled FEM-BPNN-RSM method, the authors indicated that riprap protection is able to improve the reliability index of the monopile structure. Additionally, they found that different contact mechanisms between the riprap protection and the monopile structure can largely affect the reliability index, in which the reliability index of no connection is much smaller than that of close contact. Additionally, another study [55] investigated the effect of riprap protection performance in the context of vibration and cyclic loads; these loads are caused by the combined action of turbine operation and a hydraulic regime. Riprap with a larger size has better subsidence resistance ability [55].

To identify the reliability of scour protection design, a reliability assessment can be performed by analyzing the means of the probability of failure P_f. In the presented case study by Fazeres-Ferradosa et al. [29], through performing Monte-Carlo simulations on P_f of D_{50} of armor stones, it was found that the static [30] and dynamic approaches [31] show a similar reliability level (in the order of 10^{-4}). In particular, the annual probabilities of the failure calculated from the static approach [30] are comparable to the ones provided in offshore wind standards (such as DNV-ST-0262: Lifetime extension of wind turbines) [58]. It is obvious that design Equations (1) and (2) are deterministic designs and not related to the probability of failure, a deficiency of which leads to the development of another design approach through defining a certain admissible probability of failure to obtain the design stone size [29]. Additionally, copula-based models have been also applied in the reliability assessment of dynamic scour protections by simulating a long-term correlation between significant wave heights and the peak wave periods. For instance, Fazeres-Ferradosa et al. [59] found that the duration of the dataset and the copula used to model the dependence of the sea-state parameters considerably influence the probability of failure [59]. Furthermore, metocean environmental variables are vital for obtaining the probabilities of failure of riprap protection measures [60]. For example, parameters such as multi-decadal wave hindcasts in together with relevant statistical modelling, which estimate extreme sea state characteristics, should be considered for estimating physical actions during the lifetime of OWTs. More recently, Fazeres-Ferradosa et al. [61] performed a review study highlighting available reliability assessment techniques for scour protection approaches for OWTs. To date, however, a systematic reliability assessment technique for riprap protection measures has not been made available, despite plentiful research on such approaches over the past few years.

When applying empirical scour protection design approaches derived from experiments, it should be noted that scale and model effects might influence the outcomes (and consequently, the design results) of small-scale experiments [62]. For instance, a study on the quantification of scale effects on riprap protection experiments indicated that the dynamic protection design approach provides conservative predictions of the development of shear damage in small-scale flume tests [35]. Additionally, Wu et al. [63] analyzed the uncertainty level of the scour protection damage capacity of a dynamic design approach from De Vos et al. [31] following GUM guidelines (The Evaluation of Measurement Data—Guide to the Expression of Uncertainty in Measurement) [64] and argued that a minor contribution is generated from the hydrodynamic uncertainty to total uncertainty.

Turning now to the research advancements in countermeasures (such as rock backfilling, tyre-filled net, and sand backfilling) for failure in riprap protection, it is evident that traditional rock backfilling was found to be effective in recovering protection stiff-ness and arresting future scour. A tyre-filled net is another countermeasure approach which can effectively slow the erosion process but ineffectively improve the system dynamics [65]. It has been also found that backfilling sand as a countermeasure approach can reduce the depth of the subsidence hole and the convective velocity around a vibrating monopile [66].

Figure 9 shows an illustration of novel cemented approaches, which have been increasingly applied in recent years to reinforce the strength of riprap protections, alongside the conventional method of laying stones directly. Gridded cemented riprap (GCRP) composed of loose riprap stones and cemented stone clusters was proposed and tested, highlighting that it can significantly improve the stability of riprap protections through grout spots staggered in a grid pattern (Figure 9). Furthermore, it has the advantage of keeping the flexibility of riprap layer compared with fully cemented riprap (FCRP). Notably, self-protecting underwater mortar (SPUM) relying on the addition of underwater protective agents (UPAs) to the water is suggested for GCRP underwater construction [33].

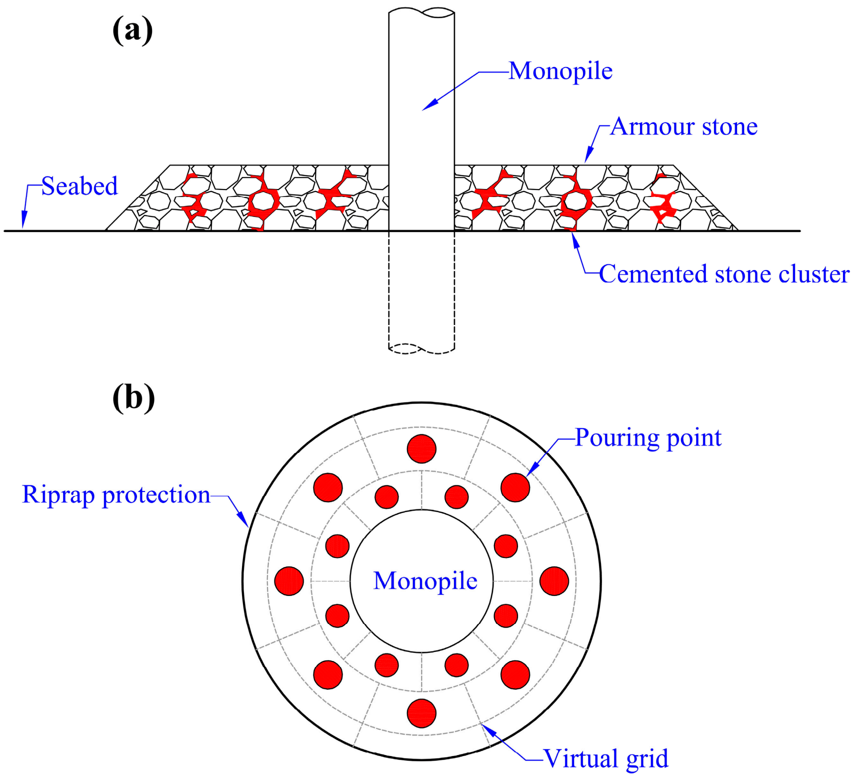

Figure 9. Grid grouting strategy of gridded cemented riprap (GCRP) (adapted from reference [33]): (**a**) Schematic of GCRP (**b**) Pouring point layout of cementitious grout at the surface of riprap.

3.1.2. Ground Improvement Protection

In addition to laying stones directly near monopile, researchers have been actively exploring the potential application of ground improvement technologies. In these approaches, scour can be restrained by (1) ground solidification by increasing the seabed density and the intensity of intergranular interactions or by (2) adding flexible coverings.

Based on the reviewed literature, we found that ground solidification measures are already widely used in architecture field, and their application to scour protection for OWTs has been studied to a certain extent. An important part of ground solidification is applying cement, can be classified by solidification constructions into two main kinds: (1) on-site combination measures described as combining the original ground materials around OWTs with solidifying materials, and (2) prefabricated mixture measures described as pumping the prepared pre-configured slurry into the required position. The solidification approach has the advantage of fewer construction materials and the disadvantage of high requirements for the appropriate design of the combination. In the case of a prefabricated mixture measure, scour protection will be formed after a slurry solidification, which can be applied to a wide range of ground conditions [67].

As for the in-site combination measures, cement-improved soil protection was tested by Ouyang et al. [68] through physical simulations under a combined action of wave and current and verified in a wind farm in Jiangsu province, China. The main components of the cement-improved soil were clay and a percentage of cement for chemical solidification. The raw materials were fully mixed as a fluid near the OWT and the mixture was pumped and flowed to the seabed surface around the monopile; then, it gradually hardened into scour protection. They concluded that the cement-improved soil approach was feasible and effective in engineering applications and provided optimal protection ranges (see [68]). Another study [67] applied sulphate aluminum cement and clay as solidified soil to form scour protection and described the microscopic mechanisms of this solidified soil. They also reported and established a relationship between its unconfined compressive strength and scour resistance parameters including critical flow velocity, equilibrium erosion depth, and equilibrium erosion volume, which is essential for solidified soil design as a form of scour protection.

As for the prefabricated mixture measures, high-pressure jet grouting of superfine cement–sodium silicate slurry (C–S) was applied to bind and solidify loosely packed particles in the seabed. It was confirmed to be more effective than riprap and collar protection (discussed in Section 3.1.3). Jet grouting was selected because of its better mixing results compared with infiltration grouting. The sequence of scouring development in this combined form of scour protection was described as cracking developing from the homogeneous seabed after grouting, peeling off grouting blocks, the incipient motion of these blocks, and abrasion from sand-laden flow [69]. Furthermore, previous studies [70,71] found that the high-pressure jet grouting measures are able to significantly increase the ultimate horizontal bearing capacity under static loads and provide more stability under cycle loads. The main reason for this strengthening effect is that the pile sediment structure is closed by grouting [70]. Moreover, the method used to determine the ultimate horizontal bearing capacity of this grouting protection was initially studied based on the limit equilibrium method [71].

Not only cement can solidify soil; microbial-induced carbonate precipitation (MICP), as an eco-friendly and low-maintenance method, can also produce spherical $CaCO_3$ crystals to form cementation blocks as a form of scour protection and seabed enhancement. MICP has proven to be effective on bridge piers [72], coastal slopes [73], and hydropower dams and dikes [74]. For scour protection of OWTs, physical model tests on MICP by Li et al. [75] showed that hemispherical scour protection formed around the monopile. The MICP protection layer size and strength can be increased by enhancing cementation through multiple MICP treatments, as illustrated in reference [75]. The construction methods of MICP suggest grouting biological and cementing solutions into the seabed for underwater operation or spraying them when the monopile foundation is exposed at low tides [75]. Additionally, enzyme-induced calcite precipitation (EICP) also has the potential to become an effective scour protection measure or a supplementary method of MICP [22]; however, this may be more expensive, with a higher treatment speed compared to MICP [76].

It is evident from the literature that flexible covering measures are mature and common approaches for soil and ground stabilization, and their applications for OWTs are discussed and studied elementarily. Geotextile sand containers (GSCs), as an improved scour protection measure based on riprap, work as a combined filter and armor system. GSCs can be installed ahead of the wind turbine structure's installation and adapt to the shape of the seabed. GSC are made of untreated, mechanically bonded non-woven elements. Plenker et al. [77] analyzed the influence of the container shape and material properties of GSCs. Later, a life cycle assessment following the cradle-to-grave approach was conducted by Hoyme et al. [78], where the authors observed the environmental benefits of GSCs. Another study [79] proposed a sand-ribbed geotextile mattress (SRGM) (Figure 10), bionic grass (discussed in Section 3.1.3), and a honeycomb grid geocell (Figure 11) as scouring protection materials. Li et al. [79] found that the SRGM coverage is the most effective scour protection method among them. The SRGM is a novel variant of a geotextile mattress, and it is a combination of high-strength geotextiles as a flexible framework and sand as a filling. One study [79] pointed out that the SRGM is very likely to have a negative impact on the local environment and species. As for honeycomb grid geocells, these small-size grids have better anti-shear and scour protection abilities than large-size grids. Benefiting from its honeycomb structure, these geocells can limit particle movement and provide space for underwater vegetation [79].

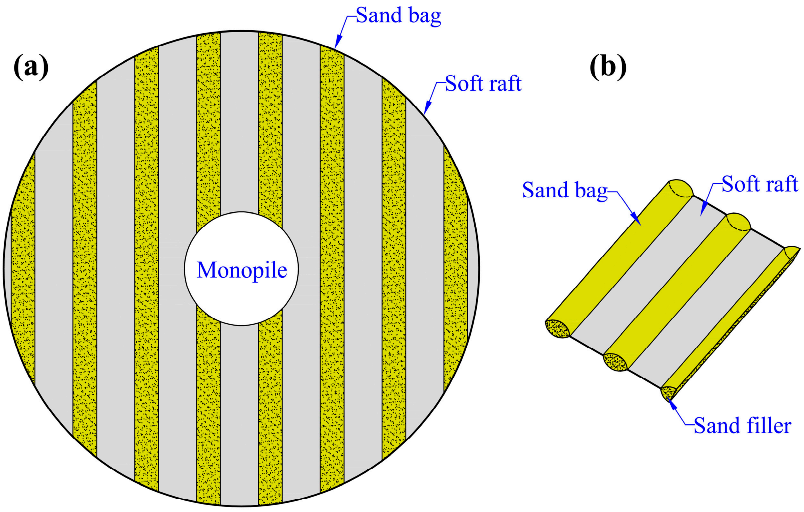

Figure 10. Sand-ribbed geotextile mattress (SRGM) (adapted from reference [79]): (**a**) SRGM layout in scour protection; (**b**) detailed design of an SRGM.

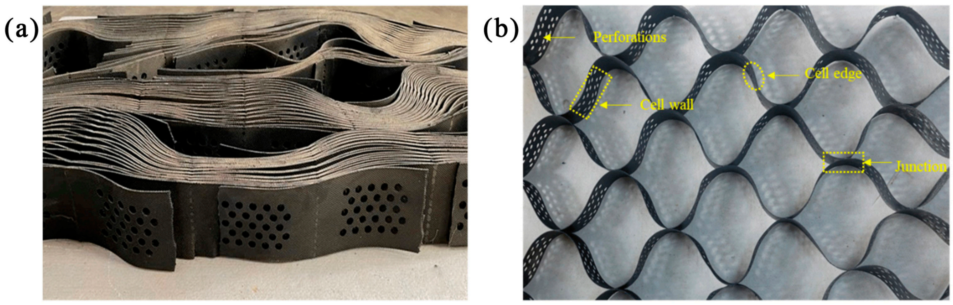

Figure 11. Honeycomb grid geocell (from reference [80]): (**a**) collapsed form; (**b**) expanded form.

3.1.3. Flow-Altering Protection

Flow-altering protection with a relatively less space occupation has attracted more attention in recent years. This type of measure aims to change the water field, which is an important element of the scour phenomenon.

Typical flow-altering protection is placed below the seabed level. Based on the selection of different collar thicknesses, collar base and collar column protection (Figure 12a,b) were studied in flume experiment under a steady current (see [81]). In their work, the collar base was placed precisely at the seabed level, and its failure was observed because of the erosion beneath the collar base, which can be mitigated by increasing the thickness of the collar base. The collar column is buried below the seabed level with a certain depth (known as the buried depth) which is able to provide space for the local scour, but edge scour may not appear due to the large buried depth and the large diameter of the collar column [81]. Based on the previous studies of collar base and collar column, Tang et al. [82] proposed a collar threshold elevation defined as the elevation where no scour can occur below the collar. The protection effect of three placement types of thin collar (Figure 12c–e) is discussed and a new prediction equation for equilibrium scour depth at a monopile with collar protection is proposed (with the limitation of clear water conditions without general scour) [82]. In addition, collars with different shapes and multi-layers have the potential to improve existing designs.

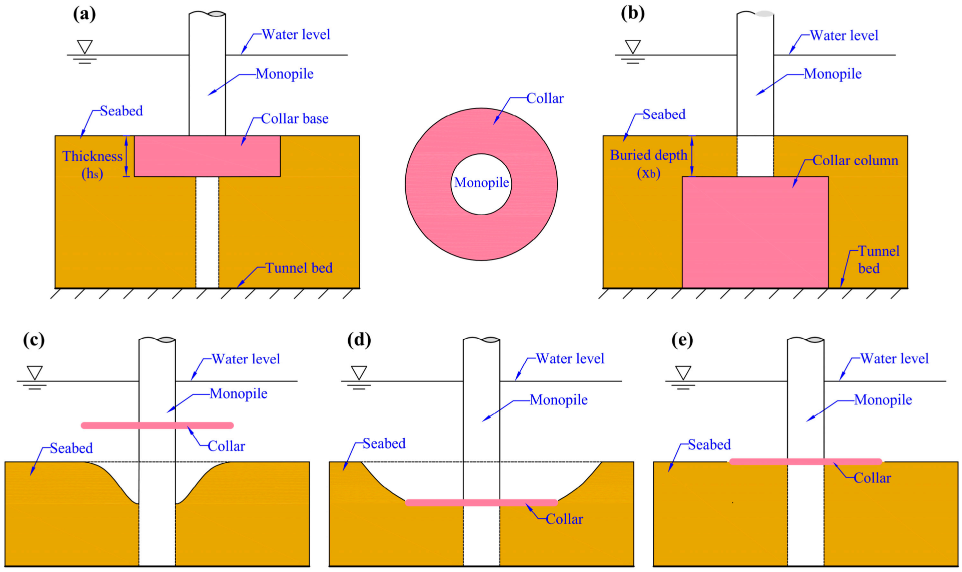

Figure 12. Collar protection (adapted from reference [81,82]): (**a**) collar base; (**b**) collar column; (**c**) collar placed above bed level; (**d**) collar placed below threshold elevation; (**e**) collar placed at bed level.

Apart from the collar, adding spoiler structures is a relatively efficient flowing-altering measure. Li et al. [83] studied a monopile with eight fixed spoiler ribs (Figure 13a) and revealed the influence of the ribs with different sizes on the horseshoe vortex and shear stress distribution around the monopile. For a 6 m diameter monopile, a spoiler rib with 1 m length and 1 to 2 m height is suggested for effective protection [83]. Considering that ribs directly connected to the monopile may cause additional stress, a transition design between the ribs may be useful. Cho et al. [26] analyzed a monopile with a quattro-pod flow-altering structure, as shown in Figure 13b. This quattro-pod structure is not considered an efficient scour protection measure because significant scattering occurred while mitigating scouring [26]. The reason for this phenomenon is probably that the four edges of this quattro-pod structure unnecessarily increase the water pressure in front and on the sides of the monopile. Thus, a horn-like scour countermeasure device (SEMCD) with the advantages of easy installation and replacement is proposed [84]. Based on its computational fluid dynamics analysis in ANSYS CFX, SEMCD is effective in cancelling down and up-flows in front of the monopile and constraining almost all horseshoe vortices on the surface of the SEMCD. Yang et al. [84] found that the maximum flow velocity reduced about 50%, the maximum shear stress reduced over 40%, and the maximum eddy viscosity reduced about 40% by using SEMCD. In addition, when the monopile diameter is 7 m, a 7 to 8 m arc curve radius of SEMCD is suggested [84]. The above spoiler structures are fixed on the monopile and probably cause a negative impact on the monopile foundation stability because of transferring non-uniform forces. A rotatable and unpowered light turbine is designed as an improvement of the spoiler blade system. A sixteen-blade light turbine, as shown in Figure 13d, is proposed to divert the incoming wave energy into mechanical energy [26]. Although it is able to mitigate the standing waves in front of the monopile, its scour protection ability is still questionable based on changes in the direction of water flow and secondary damage of the blades' rotation on the seabed below. Research for spoiler blades as a scour protection measure for OWTs is mostly numerical simulation at a preliminary stage, and further flume experiments and field tests are very necessary for understanding and evaluating their mechanism and efficiency.

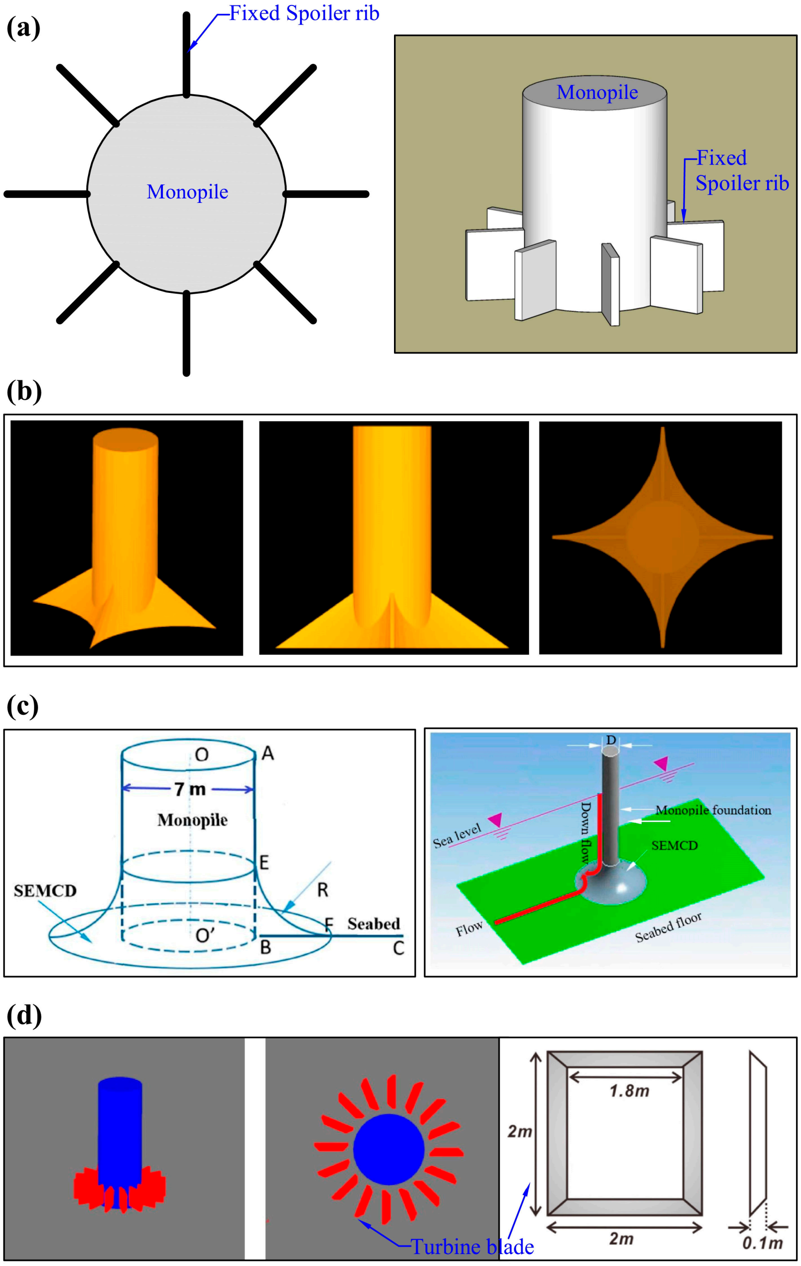

Figure 13. Spoiler structure design: (**a**) monopile with eight fixed spoiler ribs (adapted from reference [83]); (**b**) monopile with a quattro-pod structure (from reference [26]); (**c**) monopile with a horn-like scour countermeasure device (SEMCD) (from reference [84]); (**d**) monopile with a light turbine (adapted from reference [26]).

In addition, increasing the surface roughness of the monopile can reduce the energy of water flow and flow velocity. Li et al. [85] proposed sharp and round groove protection structures (shown in Figure 14a) and a bionic wave structure. Their disturbance characteristics and scouring characteristics were analyzed and compared. This bionic wave structure was found to have a good vortex-breaking effect and achieve a smaller scour depth at several measurement points. This research is only based on numerical simulations, and further parametric studies should be carried out [85]. However, it can be very expensive to safely modify the monopile surface or customize surface structure; therefore, more cost-effective methods are needed. A fishnet scour reduction technique (shown in Figure 14b) with the advantages of low cost and easy installation was studied by Wei et al. [86]. Preliminary feasibility research into this fishnet was conducted based on numerical simulation and found that the fishnet is able to disturb the path of water flow and consume the energy of downflow in front of the monopile and the vortices nearby the monopile [86]. Further research [87] reported that the maximum shear stress on the sea floor surface of the monopile can be reduced by about 14% with this fishnet device. In addition, the tidal current tank experiment in [87] showed that the largest erosion depth around the monopile can be reduced by about 38% considering the size of the fishnet, the diameter of the fishnet thread, and the length of the fishnet device. The proposed installation method is to tie the fishnet to the monopile foundation using a frogman [87].

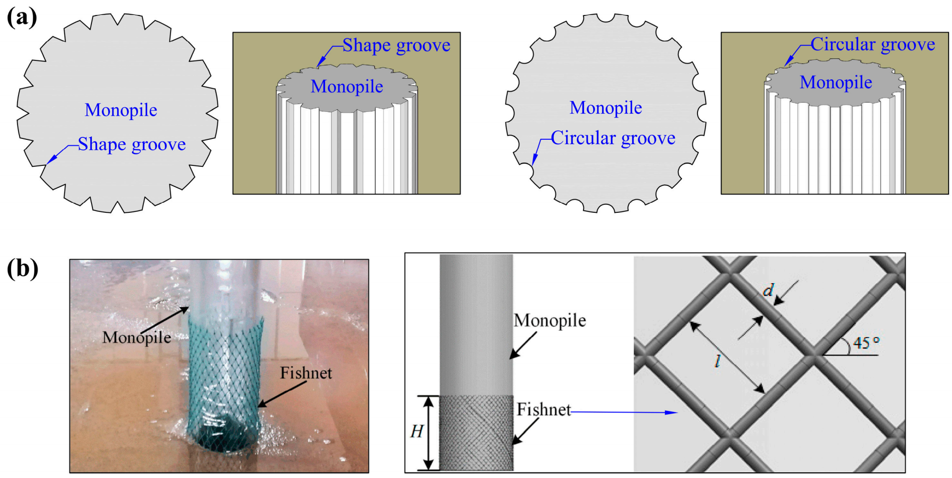

Figure 14. Designs for increasing surface roughness: (**a**) monopile with sharp and round grooves (adapted from reference [85]); (**b**) monopile with a fishnet flow-altering device (from reference [87]).

Flow-altering devices are not always closely connected to the monopile itself. According to research on the local scour protection of a submarine pipeline [88], bionic grass (shown in Figure 15) also termed fiber-reinforced mats, can reduce the flow velocity near the seabed and stimulate the deposition of the sediment by slowing down the near-bottom flow carrying a high concentration of the bed load. It is reported in inspection data that about 50% of the bionic grasses installed will be lost from the site [88]. Therefore, it is necessary to inspect the submarines' condition and add additional bionic grass as part of their maintenance. Another study [79] found that the performance of the bionic grass can be improved by increasing the width of the bionic grass vane. To reduce the loss of bionic grass and increase the ecological effect, a combination of the bionic grass and benthonic plants may be an ideal scour protection system and potential research direction.

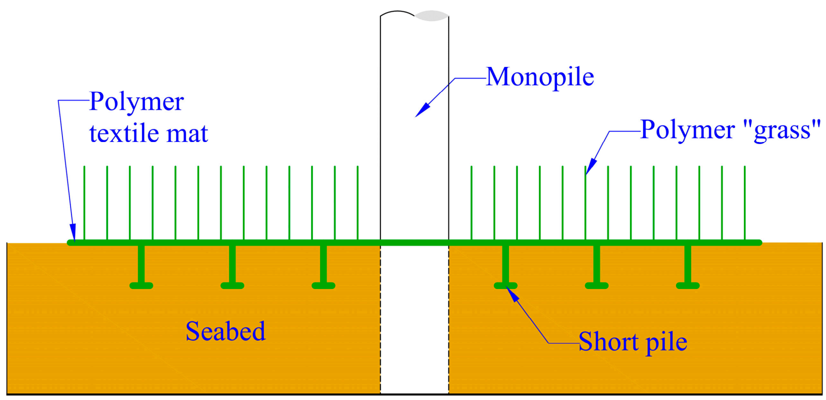

Figure 15. Bionic grass placed around the monopile (adapted from reference [79]).

Another innovative flow-altering measure is to bring other functional marine artificialities together with monopile foundations. Adding a tidal current turbine (TCT) on the monopile (shown in Figure 16a) can mitigate scouring and generate green electricity in the meantime. In this case, the TCT rotor's operation has the potential to absorb tidal current energy and disrupt water flow, which will lessen the intensity of vortices surrounding the monopile and, consequently, scouring. Both numerical simulations and a flume experiment concluded that the shear stress on the seabed surface is reduced to an extent after installing TCT [25]. However, the normal operation of TCT can be disturbed by flow asymmetry and axial yaw misalignment [89]. Notably, a TCT with limited lifespan is expensive, including upfront cost and later maintenance. Although this TCT is suspended from a rotating platform, its efficiency and input–output ratio are still challenging. In addition, a combined structure composed of a fixed monopile foundation and a bottom-seated circular aquaculture cage installed (shown in Figure 16b) on the inclined seabed was proposed by Wang et al. [90], and its effect on wave run-up along the monopile foundations was clarified. It was shown that with the enhancement of the nonlinearity of incident waves, the contribution of this aquaculture cage in damping wave loads and absorbing wave energy decreases. This research [90] also compared the damping performance of clean and fouled cages and found that the fouled cage has a greater damping effect, which is more likely to cause wave resonance between the outer cage wall and the inner monopile foundation. Aquaculture cages can coexist with creatures, and artificial reef blocks placed near the monopile can also mitigate sediment scour. Yang et al. [91] studied the effects of artificial reef blocks with various distances and arrangement forms on flow characteristics and sediment scour changes around a monopile. When the distance between the monopile and the artificial reef block was equal to the monopile diameter, a 26% reduction in scour volume was observed. The parallel arrangement of two blocks was considered to be more efficient than the tandem arrangement [91].

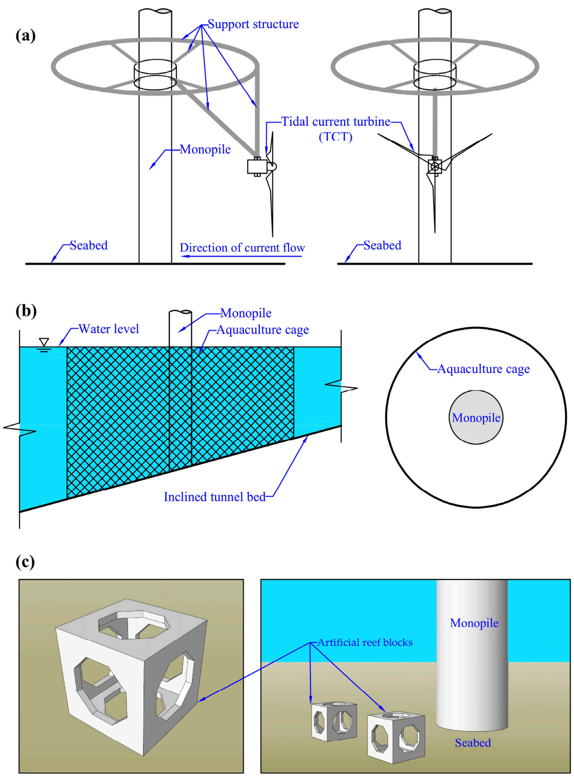

Figure 16. Functional marine artificialities combined with a monopile foundation: (**a**) monopile with tidal current turbine (TCT) (adapted from reference [25]); (**b**) monopile with an aquaculture cage (adapted from reference [90]); (**c**) monopile with artificial reef blocks (adapted from reference [91]).

3.2. Jacket Foundation

Jacket foundation is typically installed at 20–50 m water depth [9]. In the literature, there exist many forms of jacket foundation structures for OWTs, as shown in Figure 17.

The upper structures of jacket foundations can be classified as (a) three-legged jackets, (b) four-legged jackets, and (c) pentapods, without considering brace types and variety in jacket heights. The subsurface structures can be classified as multi-pile foundations and suction bucket foundations. Previous studies have investigated their hydrodynamic response (such as [92]), scour phenomena (such as [4,93–95]), and the influence of scour on the performance of jacket foundations (such as [96,97]). It is evident from the literature that the extent of scour in jacket foundations is much higher than that in monopile foundations in otherwise identical conditions; this is due to the flow resistance caused by the truss structure and the flow disturbance at the variable section of pile leg [93]. The maximum scour depth usually occurs in the up-current or up-wave side of the jacket foundation [98]. Scouring of pile group jacket foundations includes local scour at the piles and global scour underneath and around the structure's footprint [94]. As for multi-bucket jacket foundations, local scour on three-bucket jacket foundations with different heights of bucket top exceeding the seabed elevation were studied and quantified [4]. In addition, a generic calculation model was developed to efficiently estimate the local scour influence on the bear capacity of a four-bucket jacket foundation [95].

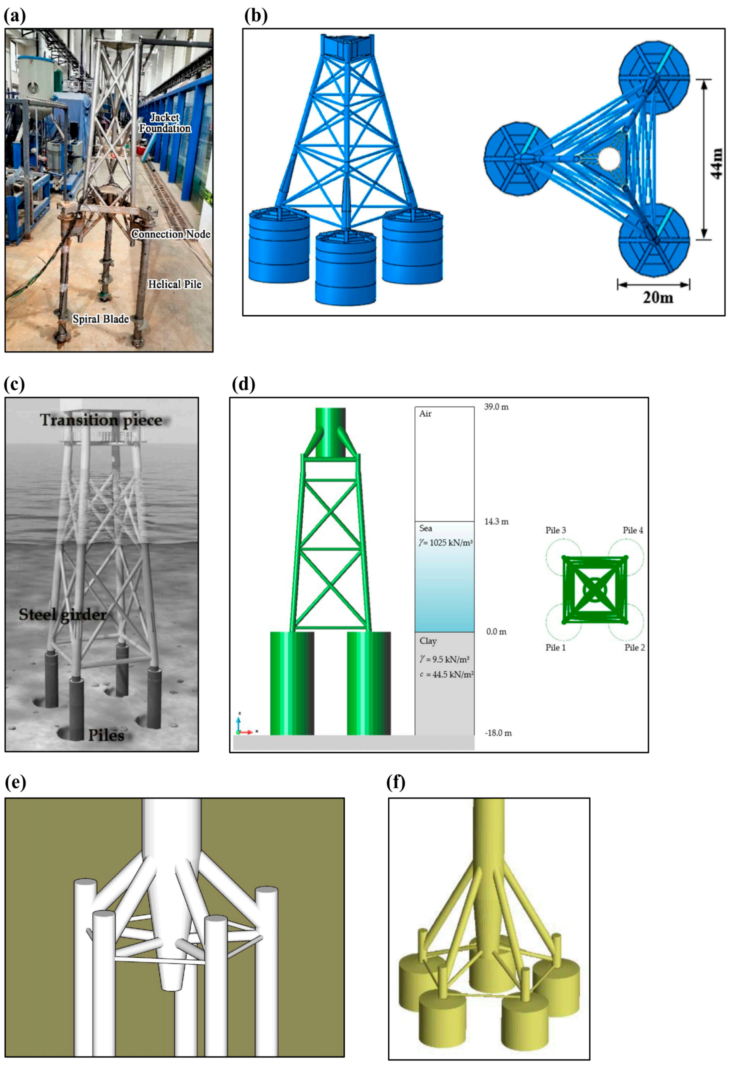

Figure 17. Different forms of jacket foundation structures: (**a**) Three-pile jacket foundation (adapted from reference [99]); (**b**) three-bucket jacket foundation (from reference [100]); (**c**) four-pile jacket foundation (from reference [101]); (**d**) four-bucket jacket foundation (from reference [102]); (**e**) five-pile jacket foundation (adapted from reference [103]); (**f**) five-bucket jacket foundation (from reference [104]).

When compared with monopiles, only a handful of studies focused on scour protections for jacket foundations. Sarmiento et al. [105] mentioned that a kind of rock protection (shown in Figure 18a) has been applied on at least one of the foundations of the wind farm East Anglia ONE (UK). The authors analyzed the falling apron effect and the stability of this rock scour protection for a three-pile jacket foundation. From the falling apron point of view, a low dependency of scour protection on hydrodynamic load history was found by the authors. In addition, the maximum deformation of the scour protection was found to be greatly affected by the arrival order of storms [105]. Another form of hard scour protection (shown in Figure 18b) with four layers for four-pile jacket foundations was proposed in [106] and found by tests to be effective in preventing scouring. This form of scour protection surrounds the outside of the jacket foundation and is in the approximate shape of a hollow square with rounded corners [106]. It is valuable to consider scour protection for all the legs as a whole instead of several individual scour protection measures for different legs. However, the inner square of this scour protection structure is unprotected, and it is very likely to be the area most impacted by erosion. Additionally, a feasibility study on an integrated jacket foundation of OWTs and mariculture cages (shown in Figure 18c) was conducted and initially found that a mariculture cage can reduce the maximum scour depth by about 36% [107].

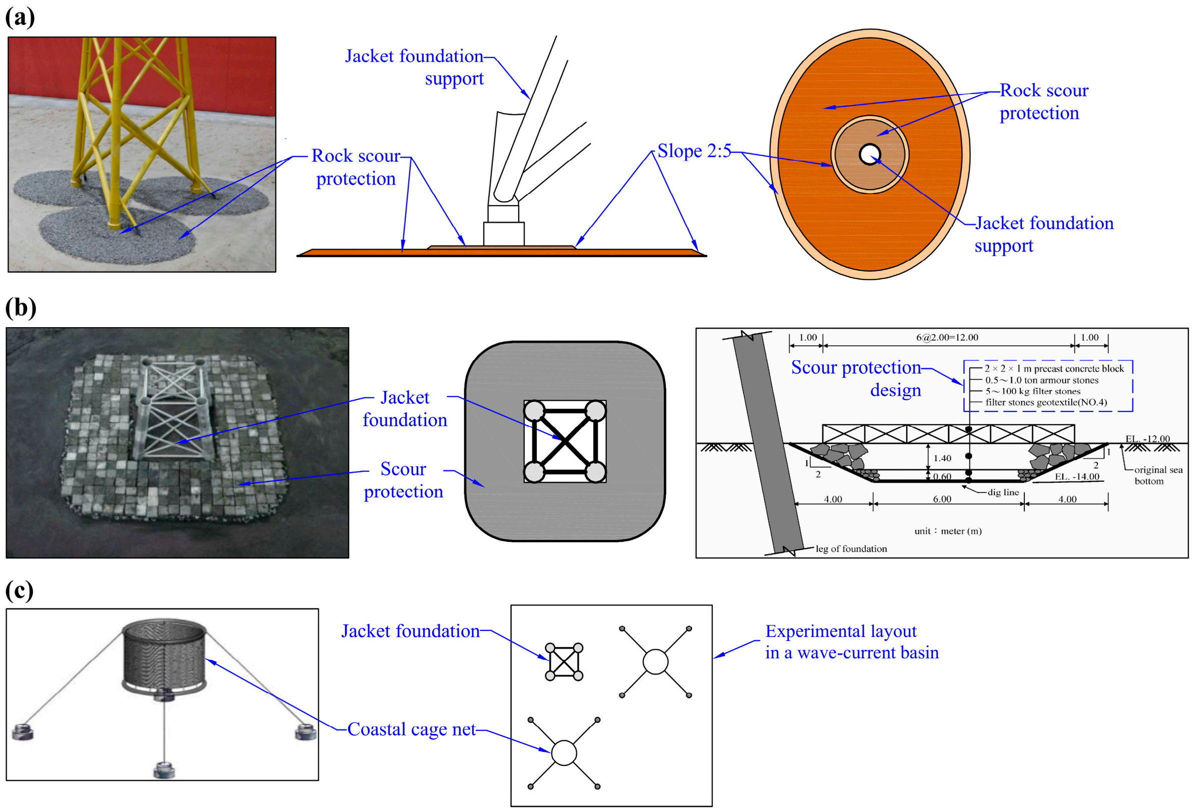

Figure 18. Scour protection design for jacket foundation: (**a**) oval rock scour protection (adapted from reference [105]); (**b**) four-layer hard scour protection (adapted from reference [106]); (**c**) jacket foundation integrated with mariculture cages (adapted from reference [107]).

3.3. Other Foundation Types

Although extensive research has been carried out on scour protection measures over the past few years, no single study focuses on other foundation types. However, we found that many scour analysis and construction research papers indirectly mentioned potential or applied scour protection measures for other foundation types. Gravity base foundations generally use riprap rock to achieve scour management [108,109]. In addition, other materials such as sand bags and concrete mattresses can be adopted [109]. Another study [110] applied rock armor protection on a suction caisson foundation and a quadruple foundation to study scour and liquefaction response on the seabed.

Considering that scour protection is an applied science, it is very likely that different types of scour protection have already been tried, designed, and applied to wind farm projects, especially for riprap protection.

3.4. Impacts of Scour Protection Measures on the Environment

Previous studies (for example [111]) have highlighted that the development of offshore wind farms may have potential ecological benefits for the surrounding environment in addition to obvious low-CO_2 energy production. Although OWTs may cause ecological disruptions (mainly including avian collisions, noise above and below water, electromagnetic fields, and loss of soft-bottom habitat with the introduction of hard substrata), the foundation of OWTs with scour protection, however, can increase the abundance and biodiversity of hard-bottom species [112]. Furthermore, based on offshore wind farm surveys, previous studies [113,114] have also revealed the ecological benefits of OWTs, such as organic enrichment, macrofauna changes and the colonization of the foundation structures. Horwath et al. [115] provided a comparison of environmental effects from different offshore wind turbine foundations and analyzed the direct and indirect effects during installation and operation. Different foundation types and scour protection measures were found to be attractive to various taxa [116], highlighting an obvious influence on offshore fishery and offshore aquaculture due to reef effects and creation of no-take zones within offshore wind farms. Glarou et al. [112] reviewed current knowledge of artificial reef designs, which is similar to scour protection and suggested a transfer of knowledge from various artificial reef design refinements to future scour protection construction. Wind farm construction and the commissioning of offshore wind farms also affect epibenthic macrofauna biodiversity [117]. Similar findings were also reported by Bull et al. [118] for the decommissioning of oil and gas platforms.

To achieve eco-friendly scour protection measures, in addition to the applied protection structure and materials, there should be attention to the site-specific environmental impacts of such measures. Nevertheless, previously published studies so far have not dealt with the environmental impacts of scour protection measures in relation to different foundation types.

4. Key Challenges and Future Research Needs

Having reviewed the existing literature, several key challenges and potential research gaps are identified in this section to form the future research directions. They are listed as follows:

First, there is a need to develop more systematic design standards/guidelines for efficient scour protection design, assessment, construction, inspection, maintenance, and decommissioning, in particular for widely used riprap protections. In addition, more considerations such as geotechnics, statistics, and spatiotemporal changes should be involved in scour protection designs. The existing scour protection design is mostly based on empirical equations and engineering judgment, which can potentially lead to design redundancy and the frequent appearance of defects.

Second, scour protection design should be integrated into the foundation design rather than being an independent design consideration. For example, Geißler et al. [119] developed a design approach applying compaction grouting for offshore pile foundations to improve pile bearing capacity, similar to soil improvement in scour protection measures; it has the potential to become an integrated monopile foundation design. Future research could be devoted to answering questions including the following How and to what extent do different scour protection measures influence the design of foundations? What are the challenges involved in developing an integrated scour protection and foundation design?

Third, a more detailed laboratory and field assessment of the trade-offs involved in any newly developed or proposed measures should be conducted. In addition to the scour protection measures discussed within this work, other potential approaches inspired by scour protection design of bridge piers are also proposed in the literature, including hinged mattresses, artificial tetrapod stones, submerged vanes, slots on monopiles, sacrificial piles, bed sills, and flow-altering surface designs [17]. Additionally, wave energy converters also have the potential to combine with OWTs to mitigate the impact of waves on structures. On top of field, laboratory, and numerical modelling, in recent years, several studies have successfully applied data-driven machine learning approaches (such as [120–122]) for the estimation of scour holes (mainly for coastal defenses), which could be further explored for scour protection design for OWTs. Nevertheless, the comparison and trade-offs of such measures may be key elements of future studies given the obvious differences between each scour protection measures and foundation types.

Fourth, when designing scour protection measures for OWTs, the influence of such measures on the environment should be taken into account properly by the relevant authorities (such as wind farm owners, designers, and developers), with a view to restoring ecosystems and enhancing positive effects on biodiversity, as also highlighted by WindEurope [123]. Key questions to be answered through performing future works include the following: To what extent do scour protection measures influence marine ecosystems? How do changes in design and the materials used for scour protection measures impact the environment? What are the key challenges involved in developing more robust and environmentally friendly scour protection measures?

Fifth, future research should be focused on developing scour protection designs or approaches by actively engaging relevant industrial stakeholders and experts. It is the case that due to a solid demand, industry is often ahead of scientific research in scour protection design as an applied science, indicating that while carrying out research works on scour protections, it is imperative that researchers are aware of the latest industrial developments in this context. For instance, what calls for special attention is that industry is results-oriented and is very likely to halt scouring through scour protection designs with both usability and acceptable cost. Scientific research therefore needs to take over to achieve more effective design, considering greater benefits; then, researchers must provide help to industries while minimizing environmental impact.

5. Conclusions

This paper systematically reviewed and summarized the key findings of the most recent works pertaining to scour protection measures applied to OWTs. The work follows a structured review framework, incorporating information from 68 peer-reviewed research publications that were selected through a set of defined screening processes. By supporting more evidence-based scour protection design guidance, this study aims to more accurately represent the key challenges and the variety of knowledge gaps related to scour protection measures for OWTs, which are applicable to different settings. Based on meta-analyses of recent twenty years' research, a comprehensive assessment of scour protection, particularly riprap protection, was conducted, and the latest advances were analyzed from a contemporary perspective. Additionally, this review work reported some of the key challenges and future research directions for addressing such challenges relating to scour protection measures for OWTs. The following conclusions can be drawn based on this systematic literature review:

- Scour protection research for monopile foundations is far ahead of research into other foundation types and contributed to more than half of the existing works on scour protections pertaining to riprap protection. When comparing design guidance for different scour protection measures, it is evident that knowledge on riprap measures is advanced and more welcomed by the offshore wind industry.
- Based on our literature review, it can be reported that previously published research works have not investigated scour protection measures for jacket foundations in great depth. Hence, there is a need to explore the suitable scour protection measures for jacket foundations and to generate design guidance for the same.

- Existing scour protection design is mostly based on empirical equations derived from laboratory and field measurements or inputs from designers. It should, however, be noted that results from laboratory experiments (such as small-scale wave-current flume tests) could be influenced by scale and model effects and therefore associated uncertainties. Additionally, more considerations such as geotechnics, statistics, and spatiotemporal changes should be involved in and implemented into the future scour protection design.
- This study also found that there is scope to integrate the design of scour protection measures with different foundation types. When designing such measures, relevant industry should be engaged to maximize their potential. This knowledge from industry is crucial for the sustainable and effective development of scour measures for OWTs, which will help to clarify the needs of stakeholders and provide valuable insights into the design approach.
- Recent works on scour protection measures highlight the potential ecological benefits of scour protection measures. More research on developing multi-functional facilities related to ecological enhancement, aquaculture industry and other marine energy harvesting technologies should be performed to gather information for the development of nature-inclusive scour protection designs for offshore wind farms, thus contributing to improved and sustainable maritime spatial planning.

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